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Study on the control of variable resistance for isokinetic muscle training system

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Abstract.
BACKGROUND: Isokinetic muscle strength training is presently the most advanced method of muscle strength training. However, the existing control schemes of the training equipment are usually limited to the structure of the brake.
OBJECTIVE: In order to solve this problem, this paper presents a solution to an isokinetic system based on the force control of a DC servomotor.
METHODS: A new fuzzy impedance nonlinear controller is designed by analyzing the relevant requirements of isokinetic motion. A series of force tracking comparison experiments between a fuzzy PI controller and a classical PI controller are studied. In addition, some strength training experiments employing different driving forces and target speeds are also conducted.
RESULTS: The results demonstrate the effectiveness of this fuzzy impedance force tracking control strategy.
CONCLUSION: Using the aforementioned methods, a comprehensive motion algorithm was designed.

Keywords: Isokinetic muscle strength training, impedance control, fuzzy control, rehabilitation training

1. Introduction

With the developments of modern rehabilitation medicine, the techniques of isokinetic muscle strength measurement and training in muscle strength recovery are garnering considerable attention. Isokinetic muscle strength training is characterized by constant speed and adjustable resistance, which results in the best effect of strength training at any position of the joint [1]. With the help of the definition of isokinetic exercise, it is apparent that, no matter how much tension muscle generates, the movements of affected limbs are always carried out at a predetermined speed [2]. Isokinetic muscle testing and training are widely used in sports medicine, orthopedics, and rehabilitation medicine. Furthermore, isokinetic exercise training was able to significantly improve chronic stroke survivors' strength and gait speed without concomitant increases in tone.

Recently, some researchers have studied an isokinetic instrument based on the principle of brakes. Dong et al. [3] proposed portable rehabilitation equipment based on a magnetorheological damper, which changes the magnetic field by means of an adaptive controller and subsequently changes the state of the magnetorheological fluid, thereby resulting in a match resistance. This new form of damper provided a

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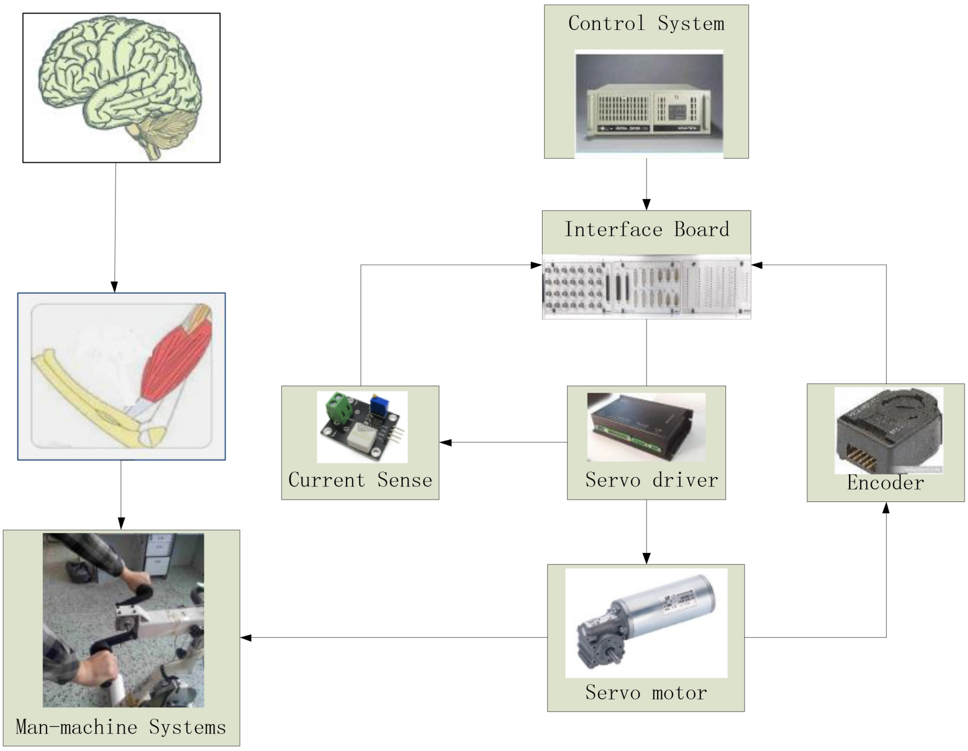

Fig. 1. The overall scheme of isokinetic training system.

new method for developing isokinetic training devices. Kikuchi et al. [4] developed an upper limb isokinetic rehabilitation device based on an electrorheological damper, and the related training effects were studied through experiments. Nikitczuk et al. [5] developed a knee rehabilitation device called AKROD, and some comparison experiments between AKROD and Biodex in isokinetic and isotonic contraction were conducted. Wang et al. [6] developed an isokinetic training device based on the principle of a throttle brake, which could change the resistance of the liquid flow by changing the orifice size of the liquid flow. Additionally, a controllable resistance, as required by isokinetic devices, can be obtained.

The aforementioned studies are all based on the principle of brakes. However, for some rehabilitation equipment, this approach will result in increased structural complexity. Therefore, this paper proposes a new muscle rehabilitation method based on the force tracking control of a DC servomotor, which benefits the expansion of isokinetic training from special isokinetic muscle training devices to external skeleton rehabilitation robots. Moreover, this method can simultaneously reduce the cost of an isokinetic apparatus, which will help promote a wide use of isokinetic training.

2. Design of rehabilitation system

The overall scheme of the isokinetic training system is shown in Fig. 1. When the user exerts a driving force on the connecting rod of the rehabilitation device, the connecting rod rotates. The speed and armature current of the servomotor are collected by using an encoder and a current sensor, respectively. Once the speed of motion reaches the target speed, the system will generate resistance to automatically maintain a constant speed. Although the user changes the joint driving torque, the control system can also rebalance the active torque and the matching torque.

There are several methods for obtaining the matching torque [7–9]; however, these methods require additional sensors to measure the relevant data. For this point, a simple and effective method is given in this paper, such that it can take a small deviation of velocity as the basis for predicting the matching torque. As for the given matching torque of tracking control, it is often indirectly implemented with a current closed loop in practice. Therefore, an integral part must be used in the force control loop [10].

3. Design of fuzzy control

The isokinetic training system is a man-machine coupling system. In the analysis, the effect of the human body on the system is simplified as the external torque.

The training system can be regarded as a mass spring damper system. The torque balance equation of the model is given below:

$$J\ddot{\theta} + B\dot{\theta} + K\theta = M \tag{1}$$

where J, B, K, and M represent the total moment of inertia, the damping coefficient, the stiffness, and the total torque of the system, respectively.

The system contains the torque generated by the motor and the external torque on the motor shaft. In addition, the effect of the heavy moment of inertia on the system is also considered. Thus, the equation can be given as follows:

$$M = M_m + M_L + M_f \tag{2}$$

where, M_m, M_L and M_f represent the motor torque, the external torque on the motor shaft and the compensating torque, respectively.

Because the system needs to provide a compliant resistance, an impedance force tracking control algorithm is used [11]. The basic equation is given below:

$$J_d(\ddot{\theta}_d - \ddot{\theta}) + B_d(\dot{\theta}_d - \dot{\theta}) + K_d(\theta_d - \theta) = M_d \tag{3}$$

where $\ddot{\theta}_d$, $\ddot{\theta}$, $\dot{\theta}_d$, $\dot{\theta}$, θ_d, and θ represent the expected acceleration, the actual acceleration, the expected velocity, the actual velocity, the expected position, and the actual position, respectively.

During isokinetic exercise, the expected acceleration is equal to zero. Because the actual acceleration is also very small, the inertia moment is ignored. Moreover, the expected position is not planned in isokinetic exercise. Furthermore, isokinetic exercise requires that the resistance be equal to zero when the speed is less than the target speed. Therefore, a nonlinear link is introduced in the impedance controller. In order to achieve optimal control, a fuzzy damping controller is designed. The impedance control equation can be modified as follows:

$$(B_d + \Delta B_d)(\dot{\theta}_d - \dot{\theta}) = M_d \tag{4}$$

According to the human skeletal muscle model, the joint torque is related to muscle force and the moment arms of joint motor tendons [12–14], which makes matching the torque more complicated. Thus, a fuzzy PI controller is adopted to more accurately track the trajectory of the joint moment. By

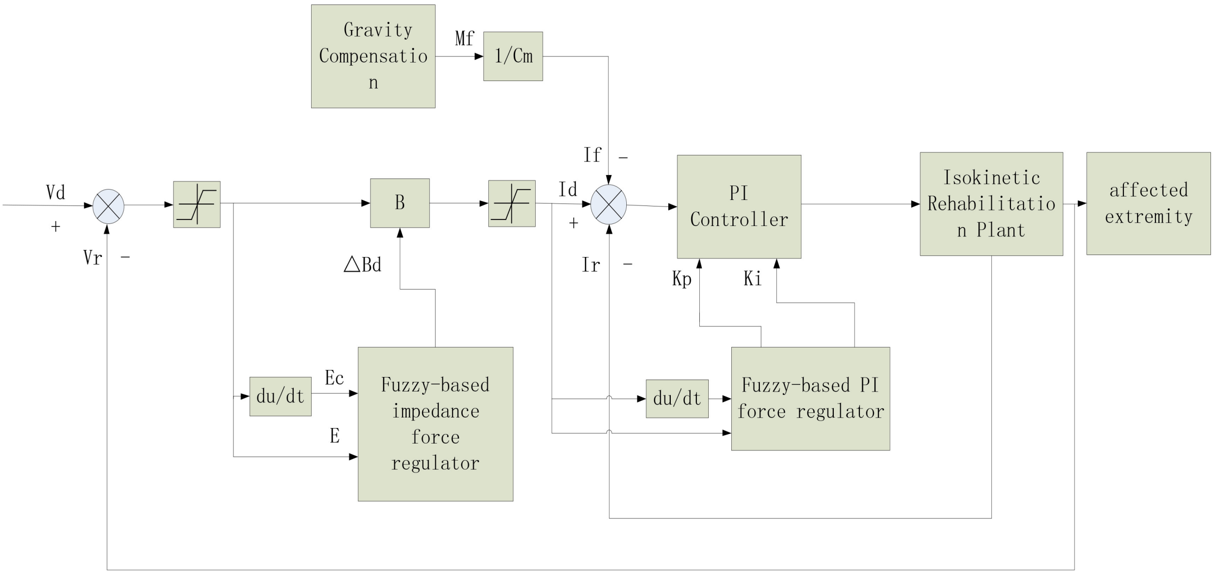

Fig. 2. The block diagram of fuzzy impedance control scheme.

controlling the armature current, the output torque of the motor is indirectly controlled. The following is the output torque equation of the controller:

$$M_d = C_m[(K_p + \Delta K_p)(I_d - I_r) + (K_i + \Delta K_i)\int(I_d - I_r)] \tag{5}$$

where, C_m, K_p, K_i, I_d and I_r represent the motor torque constant, the proportional gain, the integral gain, the given current and the fed-back current, respectively.

The structure of the fuzzy impedance controller is shown in Fig. 2. The controller includes a fuzzy impedance part, a fuzzy PI part, and a compensation link. In this paper, the experimental platform is affected by a small weight torque, so the compensation moment will be set as zero.

According to the performance requirements of the system, the domain of velocity error, the change rate of velocity error, and the increment of damping parameter are set as [−2, 0], [−0.5, 0.5], and [0, 5], respectively. The inputs of the controller are the given current and its change rate. By analyzing the optimal controller parameters for different step signals, the fuzzy rules are determined. Because the maximum output current of the motor is 6A, the domain of the given current is [−6, 0]. Combined with experience, the domain of the change rate of I_d, the domain of K_p, and the domain of K_i are set as [−0.5, 0.5], [300, 700], and [10.3, 16.5], respectively.

4. Experiments and results

This experimental platform consists of a rehabilitation device, a drive circuit, and a dSPACE HIL simulation platform, as shown in Fig. 3. The experiments are formed by a force tracking experiment and an isokinetic muscle strength training experiment, which test the performance of the inner loop and outer loop, respectively.

Table 1
Statistical results of current tracking experiments with different control algorithms

Subject	Controller type	0.2 A	1 A	2 A	3 A	4 A	5 A
Maximum overshoot (%)	PI	0	1	0	0	13	20
	FPI	0	4	3	1.5	3	2
Rise time (ms)	PI	450	200	70	150	50	70
	FPI	130	50	60	60	50	80

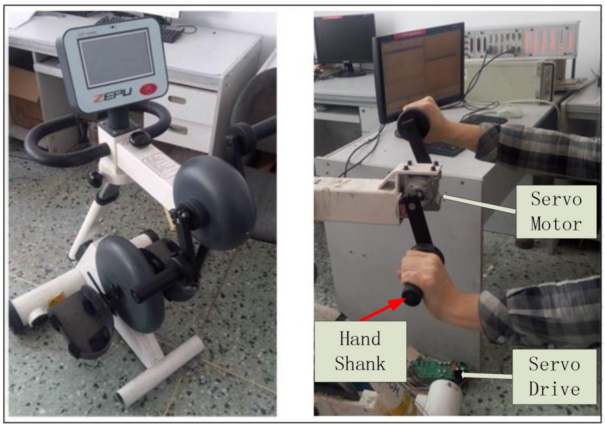

Fig. 3. Isokinetic training platform.

4.1. Force tracking experiment

The force tracking experiment is primarily used to test the response of the controller under different step signals. The classic PI controller is selected as the comparison group. The proportional gain and the integral gain of the classic PI controller are 540 and 13.3, respectively. The domain of I_d determines the amplitude of the step signal, which is set to 0.2 A, 1.0 A, 2.0 A, 3.0 A, 4.0 A, and 5.0 A. The responses are shown in Fig. 4, and Table 1 displays the overshoots of the response and the rise times.

In Table 1, it can be seen that neither the response of the FPI controller or the PI controller overshoot when the step signal is 0.2 A, and the rise time of the PI controller is 450 ms, which is much longer than the rise time of the FPI controller. When the given current is set to 1 A, 2 A, and 3 A, the maximum overshoot of the PI controller is less than 1%, but the rise time of the FPI controller is better. When the given current is set to 4 A and 5 A, the maximum overshoot of the PI controller reaches 13% and 20%, respectively, beyond the reasonable range of the system. As mentioned above, there is evidence that the FPI controller is better than the PI controller.

4.2. Isokinetic training experiment

The isokinetic training experiment is used to verify the effectiveness of the control algorithm. Taking into consideration the reliability and the feasible operability of the experiment, three muscular, healthy males are chosen as the experimental subjects. Their ages are 24, 25, and 26 years old. The experiment consists of two parts. During the first part of the experiment, the subject shakes the handle using the different force, and the target speed is set as 20 r/min. The response is shown in Fig. 5.

Figures 5(a) and (d) show that when the given current remains around 1.5 A, the speed error fluctuates between −5% and 0%. As shown in Figs 5(b) and (e), when the given current maintains around 2.5 A,

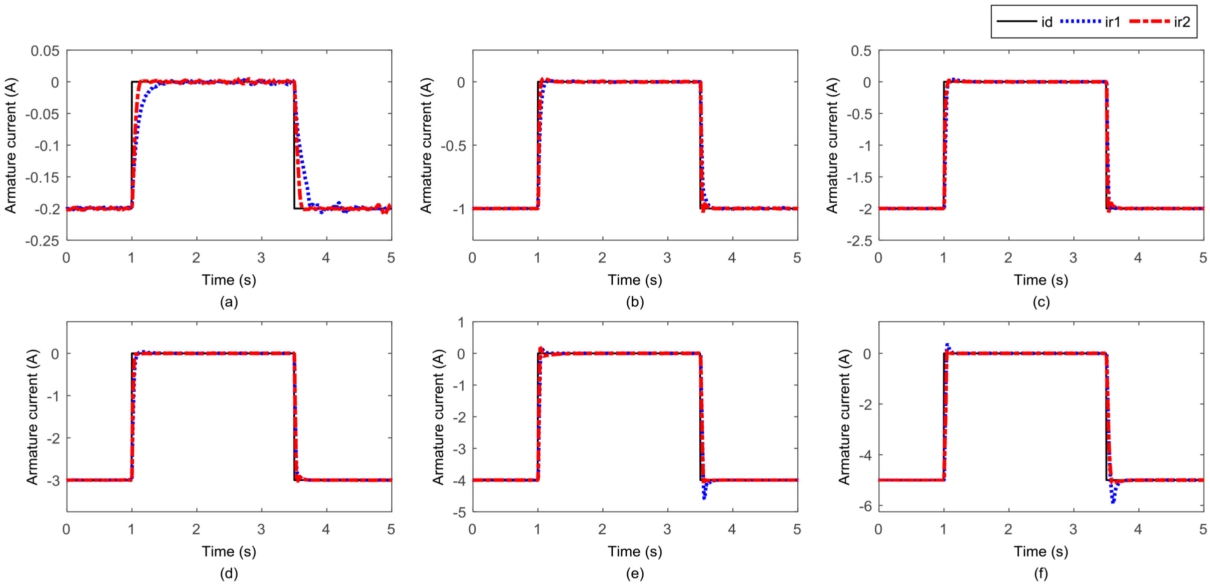

Fig. 4. Results of the current tracking experiments. Amplitude is set at (a) 0.2 A, (b) 1.0 A, (c) 2.0 A, (d) 3.0 A, (e) 4.0 A, and (f) 5.0 A.

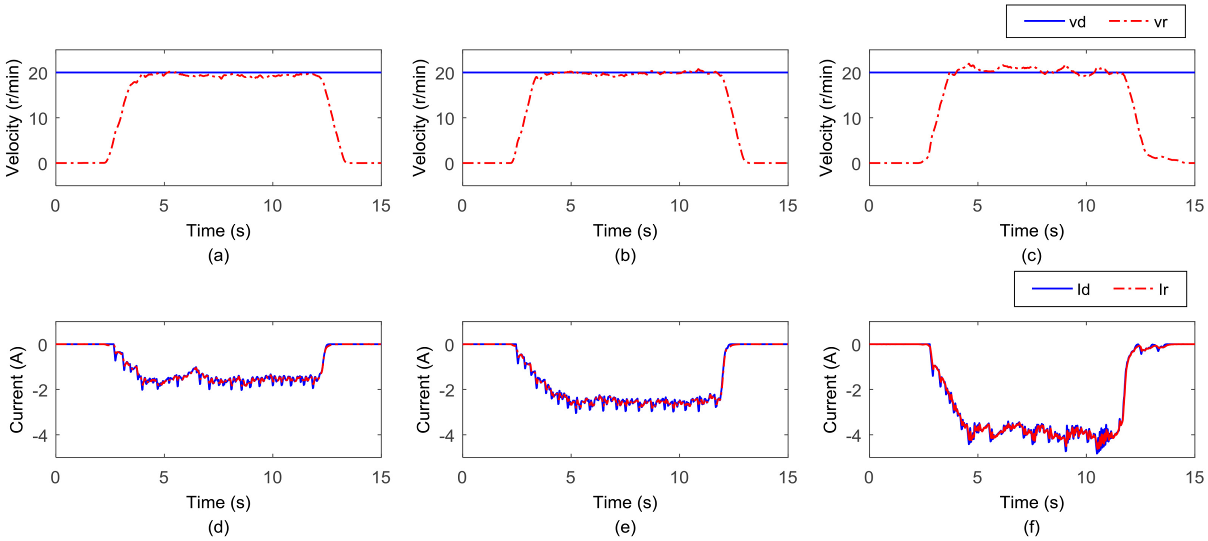

Fig. 5. Results of the first part of the isokinetic training experiment. (a) The speed of a lesser torque. (b) The current of a moderate torque. (c) The speed of a larger torque. (d) The current of a lesser torque. (e) The speed of a moderate torque. (f) The current of a larger torque.

the speed deviation fluctuates between −5% and 2.5%, and the error change rate is also fairly small. As depicted in Figs 5(c) and (f), when the given current remains 4 A, the speed deviation fluctuates between −2.5% and 10%, and the change rate is relatively large. Throughout the above data, when the given current is 1 A or 2.5 A, the speed is relatively stable, and the current follows better. When the given current remains at about 4 A, the velocity deviation becomes large, and a relatively large fluctuation

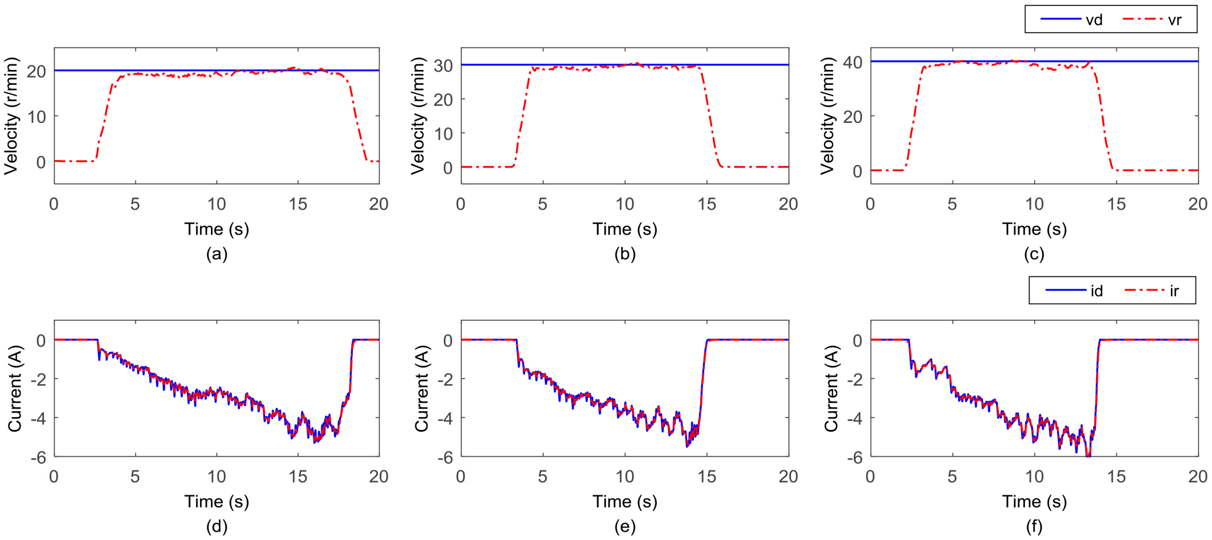

Fig. 6. Results of the second part of isokinetic training experiment. (a) The speed that target speed is set to 20 r/min. (b) The speed that target speed is set to 30 r/min. (c) The speed that target speed is set to 40 r/min. (d) The current that target speed is set to 20 r/min. (e) The current that target speed is set to 30 r/min. (f) The current that target speed is set to 40 r/min.

is generated. In Fig. 5(f), the current tracking error becomes large. This is because the response speed of the system is slow when the given current is large. The experimental results verify the ability of the system to maintain a certain speed with different external forces.

In the second part of this experiment, the target speed is set as 20 r/min, 30 r/min, and 40 r/min, and the driving force is changed from small to large. The control effect is shown in Fig. 6.

As shown in Figs 6(a) and (d), when the target speed is set at 20 r/min and the given current gradually increases, the speed deviation remains in the $-5\% \sim 1.5\%$ range, and the change rate is very small. Figures 6(b) and (e) reveal that when the target speed is set to 30 r/min, the speed error fluctuates between -5% and 1%. As depicted in Figs 6(e) and (f), when the target speed is set to 40 r/min, the speed deviation fluctuates between -2.5% and 0%, and the change rate is relatively large. The above analysis demonstrates that speed deviation remains within a reasonable range, and the speed remains relatively stable with a gradual increase in active torque. Throughout the cases at different target speeds, the results also reveal that the velocity deviation remains within an allowable range. The experiments further verify the ability of the system to maintain a target speed.

5. Conclusions and future works

The traditional control strategy of an isokinetic muscle strength training instrument is limited to the structure of the brake. This paper, however, presents a new solution for solving this problem for isokinetic systems, and this new method is based on the force control of a DC servomotor. A fuzzy impedance force tracking controller is proposed in this new scheme, and the real-time adjustment of system resistance ensures that the system speed is essentially equal to the given speed. Then, a series of force tracking experiments and isokinetic muscle strength training experiments were conducted, and the results demonstrate the effectiveness of the control strategy.

Future work will focus on the inspection and improvement of the control effect because there is a ripple in the system when the external force is larger, and the change rate of the velocity deviation increases.

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Conflict of interest

None to report.

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